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14. ABSTRACT

The objective of the project is to develop silicon-based group IV heterostructure lasers by the incorporation of anoth er group IV element of Sn. We have made significant progress toward the milestones described in the proposal. Not able achievements are: (a) direct bandgap group IV materials (cooperated with Sn) is achieved and the first state-of -the-art group IV light-emitting diode (GeSn p-i-n) operated at near infrared with direct emission is demonstrated (A ppl. Phys. Lett. 102, 182106 (2013). Editor's Picks on Semiconductor Research from APL (2014).), and (b) photodet ector with best clarity around the near to mid-infrared region is illustrated (Appl. Phys. Lett. 103, 231907 (2013), and references within). Our researches are a major milestone towards the realization of the group IV based photonic d evices

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Abstract:

The objective of the project is to develop silicon-based group IV heterostructure lasers by the incorporation of another group IV element of Sn. We have made significant progress toward the milestones described in the proposal. Notable achievements are: (a) direct bandgap group IV materials (cooperated with Sn) is achieved and the first state-of-the-art group IV light-emitting diode (GeSn p-i-n) operated at near infrared with direct emission is demonstrated (Appl. Phys. Lett. 102, 182106 (2013). **Editor’s Picks on Semiconductor Research from APL (2014)**.), and (b) photodetector with best clarity around the near to mid-infrared region is illustrated (Appl. Phys. Lett**. 103**, 231907 (2013), and references within). Our researches are a major milestone towards the realization of the group IV based photonic devices.

This report is organized as following four sections:

(a) Material growth

(b) Results on GeSn p-i-n double heterostructure on Si wafer for photonic devices

(c) Publications

(a) Material growth

On the material growth, different structures are grown by molecular beam epitaxy. First, we investigate different type of doping in GeSn alloy for serving as p- and n-type dopant. Magneto-Hall measurement is performed to identify the dopant. Then, we proceed with optical emitter made of P-i-N diode using the growth techniques of low temperature growth and virtual buffer. (For a detail description of these techniques, see Local intermixing on Ge/Si heterostructures at low temperature growth, H. H. Cheng, W. P. Huang, V.I. Mashanov, and G. Sun, J. Appl. Phys. 108, 044314 (2010).) The device consists of four layers: (a) a Ge layer grown at low temperature, (b) a n-type GeSn virture substrate, (c) Ge layer grown at a normal temperature of 600°C and, (d) a p-type GeSn layer. The lattice constant of Sn is about 15% larger than that of Ge. As a result, the Ge layers is tensily strained. Layer (b) and (d) serves as electrical contact for the diode. Systematic investigation is performed on various Sn compositions in order to obtain the structure with a direct-bandgap emitting layer [1, 2].

(b) Results on GeSn p-i-n double heterostructure on Si wafer for photonic devices

After establishing the growth technique and the critical Sn content for the direct bandgap group IV materials, we forward to the photonic devices of for mid-infrared optical emitter and detector. **Mid-infrared LED with direct emission around 2 μm and photodetector with best clarity at near to mid-infrared were demonstrated [3, 4].**

Different types of structures have been designed and we found that the double heterostructure (DH) p-i-n diode gives the best results. The DH consists of an intrinsic Ge/$Ge_{1-x}Sn_x$/Ge layers sandwiched between two Ge cladding layers that are doped either n- or p-type on a Si substrate. A schematic plot of the structure is depicted in Figure1(a). The Sn content in the active layer in this work has reached 7.8%, representing a step forward from previously reported GeSn EL structures for the direct bandgap GeSn diode, and the DH has the advantage of confining carrier in the active $Ge_{0.922}Sn_{0.078}$ layer.

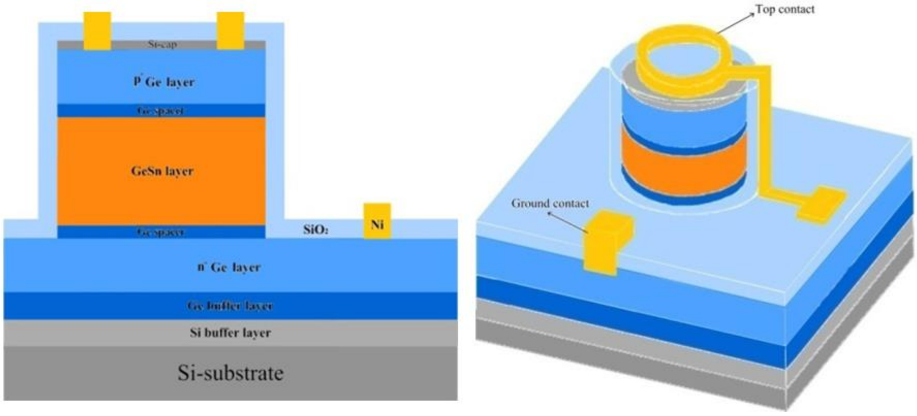

Fig. 1. Schematics of (a) cross section and (b) perspective view of the Ge/$Ge_{0.922}Sn_{0.078}$/Ge DH p-i-n diode grown on top of a Ge buffer layer on Si substrate.

(b-1) mid-infrared light-emitting diode

A typical emission spectra is plotted in figure 2. Two resolvable features start to emerge at the injection current density of 318 A/cm2. With the increase of current, they progressively develop into two well-distinguished emission peaks located separately at 0.545 eV (2.275 μm) and 0.573 eV (2.164 μm) as the injection current density reaches 490 A/cm^{-2}. The two distinguished peaks are associated with transitions of indirect and direct bandgaps of $Ge_{0.922}Sn_{0.078}$. While 7.8% is within the range of Sn content that is expected for the indirect-to-direct transition in $Ge_{1-x}Sn_x$, the EL spectra suggest that the $Ge_{0.922}Sn_{0.078}$ active layer remains indirect since the two distinguished peaks attributed to indirect and direct transitions have comparable intensities, and had it been direct, we should have seen the peak of direct transitions far exceeds that of indirect. We thus assign the 0.545 eV peak to the indirect gap while that of higher energy at 0.573 eV to the direct gap.

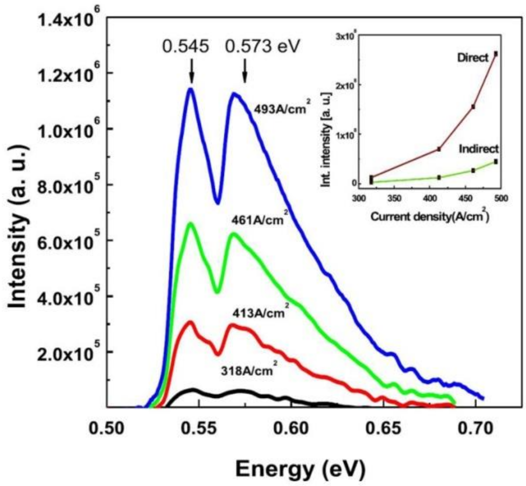

Fig. 2. EL spectra collected from the surface of the Ge/Ge0.922Sn0.0$_{78}$/Ge DH under various injection current densities. Inset: integrated EL intensities of direct and indirect bandgaps vs. injection current density.

Theoretical modeling is also performed and the result shows a good agreement with the observation. The emission spectra under various injection current densities are consistent with the expected bandgap and L-Γ CB energy valley separation reduction. The Sn content of 7.8% in our DH diode represents a sizable step towards the demonstration of an efficient direct bandgap GeSn light emitting device as compared to the reports from other groups.

(b-2) Photodetector

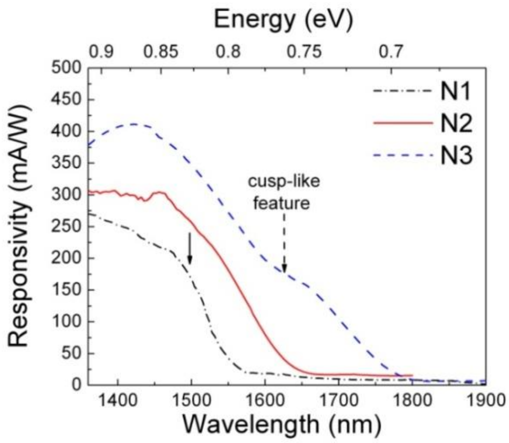

Fig. 3. The responsivity of two samples together with Ge-based p-i-n diode

Using a similar structure, high efficiency infrared detectors capable of operating ~2 μm is also demonstrated. We have made p-i-n Ge/GeSn/Ge double heterostructure detectors with GeSn layer being fully strained on Ge-buffered Si substrate grown by molecular beam epitaxy. The results are plotted in figure 3. The result shows that (a) around λ=1.5 μm, the responsivity is higher than our control sample which is a Ge detector, and (b) our detection range extends to much longer wavelength beyond λ=1.8 μm due to the smaller bandgap of GeSn alloy.

We have summarized the reported results from different groups listed in Table I [5, 6, 7]. Our investigation on strained active GeSn layers shows a larger response (per unit length of the active layer) compared to previous studies that were based on either fully or partially relaxed structures.

Table I: Responsivity of GeSn photodetectors taken from different groups. R[our sample] denotes the results from our investigation.

	R[Ref 5]	R[Ref 6]	R[Ref 7]	R	R[our sample]
Sn content	2%	3.6%	4%	1.78%	3.85%
GeSn Film	350nm	750nm	300nm	300nm	300nm
1550 nm	0.113 (0V)	0.275 (0V)	0.178	0.181 (0V)	0.272 (0V)
1640 nm	0.080 (0V)	0.255 (0V)	0.162	0.028 (0V)	0.166 (0V)
1700nm	0.069 (0V)	0.28 (0V)	0.145	---	0.104 (0V)
1800 nm	---	0.325 (0V)	0.096	---	0.08 V)

(c) Publications

(1) Formation of Ge-Sn nanodots on Si(100) surfaces by molecular beam epitaxy, Vladimir Mashanov, Vladimir Ulyanov, Vyacheslav Timofeev, Aleksandr Nikiforov, Oleg Pchelyakov, Ing-Song Yu and Henry. H. Cheng, Nanoscale Research

Letters, Vol. 6, p. 85. (2011).

(2) Investigation of Ge1-xSnx/Ge with high Sn composition grown at low-temperature, I. S. Yu, T. H. Wu, K.Y. Wu, H. H. Cheng, V. I. Mashanov, A. I. Nikiforov, O. P. Pchelyakov, and X. S. Wu, AIP ADVANCES **1**, 042118 (2011).

(3) Mid-infrared electroluminescence from a Ge/$Ge_{0.922}Sn_{0.078}$/Ge double heterostructure p-i-n diode on a Si substrate, H. H. Tseng, K. Y. Wu, H. Li, V. Mashanov, H. H. Cheng, G. Sun and R. A. Soref, Appl. Phys. Lett. **102**, 182106 (2013). Editor's Picks on Semiconductor Research from APL (2014)

(4) GeSn-based p-i-n photodiodes with strained active layer on Si wafer, H. H. Tseng, H. Li, V. Mashanov, H. H. Cheng, Guo-En Chang, G. Sun and R. A. Soref, Appl. Phys. Lett**.** **103**, 231907 (2013).

(5) M. Oehme, M. Schmid, M. Kaschel, M. Gollhofer, D. Widmann, E. Kasper, and J. Schulze, Appl. Phys. Lett. **101**, 141110 (2012).

(6) D. Zhang, C. Xue, B. Cheng, S. Su, Z. Liu, X. Zhang, G. Zhang, C. Li, and Q. Wang, Appl. Phys. Lett. **102**, 141111 (2012).

(7) R. Roucka, J. Mathews, C. Weng, R. Beeler, J. Tolle, J. Menéndez, and J. Kouvetakis, IEEE J. Quantum Electron. **47**, 213 (2011).